

On the implementation of CVC in weak charged-current proton-neutron transitions

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Abstract

It is shown that the standard expression of the vector part of the hadronic matrix element in weak charged-current proton-neutron transitions is in agreement with the CVC hypothesis, contrary to a different claim in a recent paper.

It has been argued in Ref. [1] that the conserved vector current (CVC) hypothesis [2] implies a vector current in weak charged-current proton-neutron transitions which is different than the usual one (see, for example, Ref. [3]).

Let us consider the inverse neutron decay process considered in Ref. [1]:

$$\bar{\nu}_e + p \rightarrow n + e^+. \quad (1)$$

The vector part of the hadronic matrix element has the general form (see, for example, Ref. [3])

$$\langle n(p_n) | v^\mu(0) | p(p_p) \rangle = \bar{u}_n(p_n) \left[\gamma^\mu F_1(q^2) + \frac{i \sigma^{\mu\eta} q_\eta}{2m_N} F_2(q^2) + \frac{q^\mu}{m_N} F_3(q^2) \right] u_p(p_p), \quad (2)$$

where $m_N \simeq 939 \text{ MeV}$ is the average nucleon mass, $q = p_n - p_p$ is the four momentum transfer and $v^\mu(x)$ is the vector part of the quark charged current:

$$v^\mu(x) = \bar{d}(x) \gamma^\mu u(x). \quad (3)$$

The form factors $F_1(q^2)$, $F_2(q^2)$ and $F_3(q^2)$ are called, respectively, vector, weak magnetism and scalar. The scalar form factor $F_3(q^2)$ is generated by a second-class current [4] and is well-known to vanish under the CVC hypothesis, which is a consequence of the invariance of strong interactions under isospin transformations (see, for example, Ref. [3]). The scalar form factor $F_3(q^2)$ has also been severely limited experimentally. A recent survey of superallowed nuclear β decays in which q^2 is very small found [5]

$$|F_3(0)| < 0.0035 \frac{m_N}{m_e} |F_1(0)| \quad (90\% \text{ C.L.}). \quad (4)$$

In Ref. [1] second class currents are claimed to be neglected, but it is argued that the CVC hypothesis leads to an additional term multiplying $F_1(q^2)$ in Eq. (2). It is shown in the following that this additional term is just the second class current that was supposed to be neglected, leading to a contradiction.

The implementation of the CVC hypothesis in Ref. [1] is done by assuming the current conservation relation

$$\partial_\mu v^\mu(x) = 0, \quad (5)$$

which implies

$$\langle n(p_n) | q_\mu v^\mu(0) | p(p_p) \rangle = 0. \quad (6)$$

Then, from Eq. (2) we get the constraint

$$F_3(q^2) = -\frac{m_N}{q^2} (m_n - m_p) F_1(q^2). \quad (7)$$

Inserting this value of F_3 in Eq. (2), we obtain

$$\langle n(p_n) | v^\mu(0) | p(p_p) \rangle = \overline{u}_n(p_n) \left[\left(\gamma^\mu - \frac{q^\mu}{q^2} \not{q} \right) F_1(q^2) + \frac{i \sigma^{\mu\eta} q_\eta}{2 m_N} F_2(q^2) \right] u_p(p_p). \quad (8)$$

This is the expression for the matrix element $\langle n(p_n) | v^\mu(0) | p(p_p) \rangle$ which is claimed in Ref. [1] to be correct under the CVC hypothesis.

Note the contradiction with the initial statement in Ref. [1] that the contribution F_3 of second class currents is neglected. Moreover, it is clear that Eq. (8) cannot be correct, because:

1. The CVC hypothesis based on the invariance of strong interactions under isospin transformations implies that $F_3(q^2) = 0$, not the value in Eq. (7).
2. The value of $F_3(0)$ in Eq. (7) diverges at $q^2 \rightarrow 0$, in sharp contradiction with the experimental bound in Eq. (4). For example, in neutron decay we have $q^2 \sim (m_n - m_p)^2$ and Eq. (7) would give $|F_3(0)| \sim 0.4 m_N |F_1(0)| / m_e$.

Then, one can ask what is wrong with the argument in Ref. [1]. The mistake is in assuming the exact validity of the current conservation relation (5), which is not correct, because isospin symmetry is broken by the mass difference of the u and d quarks and by electromagnetic interactions. Indeed, one can find that

$$\partial_\mu v^\mu(x) = i(m_d - m_u) \bar{d}(x) u(x) - i e \bar{d}(x) \not{A}(x) u(x), \quad (9)$$

where e is the elementary electric charge and $A^\mu(x)$ is the electromagnetic field.

Therefore, one can use the current conservation relation (5) only in the approximation of exact isospin invariance, which is equivalent to neglect the difference of the proton and neutron masses in Eq. (7), leading to the correct well-known CVC result $F_3(q^2) = 0$.

In conclusion, I have shown that the standard expression of the vector part of the hadronic matrix element in weak charged-current proton-neutron transitions is in agreement with the CVC hypothesis, contrary to the claim in Ref. [1].

References

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